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PRELIMINARY ANALYSIS OF SELECTED GAS DYNAMIC PROBLEMS

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FOREWARD AND SUMMARY

A preliminary investigation of two gas dynamic problems of interest to the Space Shuttle program was conducted. The problems were:

- SSME main combustion chamber start transients
- IUS flow field for a damaged nozzle

These preliminary studies were undertaken in order to better understand the gas dynamic considerations involved in vehicle problems; the effect of start transients on the nozzle flowfield for the SSME, and the possibility that a damaged nozzle could account for the acceleration anomaly noted on an IUS burn.

1. INTRODUCTION

1.1 SSME Main Combustion Transients

For long duration burns for engines such as the SSME, the start-up transients have very little to do with overall propulsive performance. Interest in transients for such motors is therefore only due to the structural loads which may develop. Two basic features may be expected during the start transient operation: (1) blast overpressure caused by the ignition shock wave and (2) temporary separation phenomena which occurs during combustion chamber pressure build up.

Analysis of the SSME indicates that the blast overpressures are very weak insofar as the alteration in nozzle loads is concerned, although very important with regard to the potential for damage to the vehicle. In general, the larger the volume of the engine, the slower the thrust buildup and such is the case with the SSME. The starting shock wave thus clears the nozzle before significant thrust build-up has occured.

This slow build-up, although reducing the stresses due to starting shock passage, makes separation virtually inevitable, and separation can cause very large stresses in the nozzle due to the inherently unsteady nature of the phenomena. Indeed, separation does occur in the SSME start transient.

In ground-based static tests the reverse problem can occur during shutdown; that is, separation can again occur. The separation phenomena may show some hysteresis and, as previous testing has shown, the SSME does exhibit this behavior.

1.2 The IUS Nozzle Flow

The IUS problem apparently involved a burn anomaly in which a pitch torque was created which was beyond the capability of the control system to overcome yet, towards the end of the burn, acceleration characteristics approached normal. The question was: what kind of single failure mode could have caused the torque and yet returned to a semblance of normal burn later?

Three failure mechanisms were investigated: (1) that one or both of the IUS nozzle extensions did not deploy properly, (2) that a hole opened up in the primary nozzle (in a previous test such a failure occurred) and, (3) that a portion of the grain was dislodged and exited the motor.

The results of an investigation of these two problems are presented in this report.

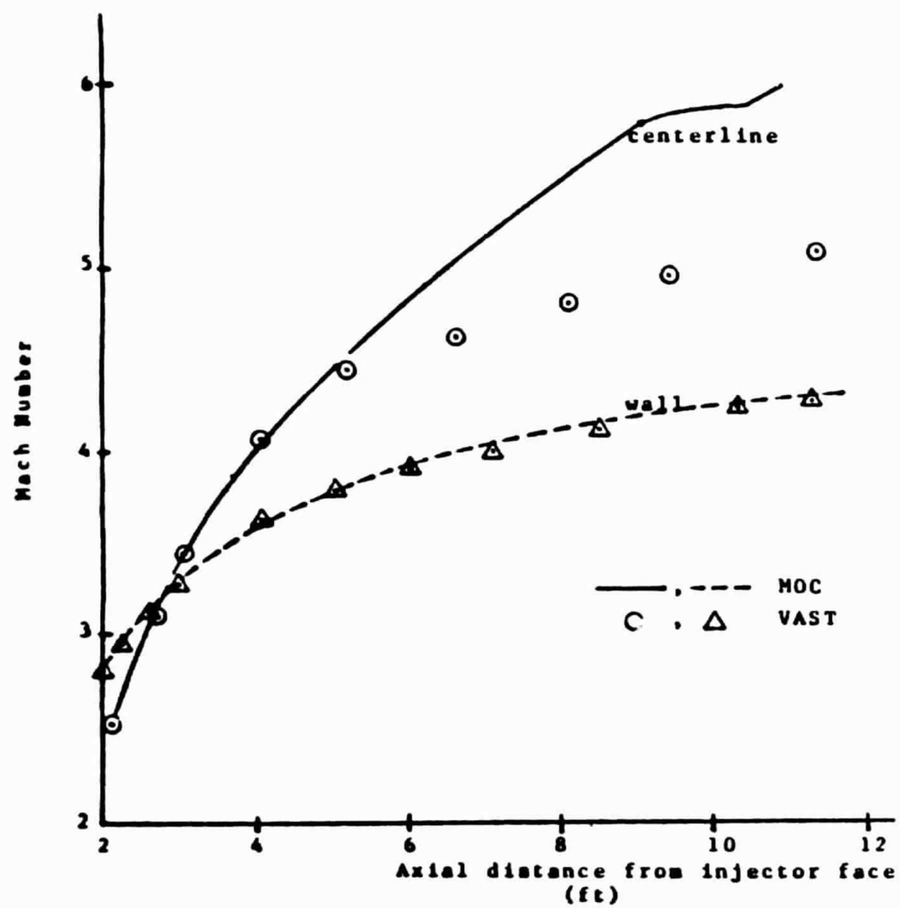
2. SSME MAIN COMBUSTION TRANSIENTS

A transient analysis of the SSME start-up was set up redundant using Continuum's VAST code. Analytical capability to describe unsteady, two - and three-dimensional flow within a thrust chamber and an expansion nozzle requires the numerical solution of the governing conservation equations with a very robust, efficient computer code. Due to the complexity of real engine systems, the operating conditions which control chamber pressure and propellant flowrates cannot be simply characterized and used as unsteady boundary conditions. For an ideal gas simulation of axisymmetric flow in a cylindrical combustion chamber, the total conditions and an additional variable must be specified. In conventional steady-state analysis, the throat choking condition is used to determine the mass flow, thus determining the system. For transient flow, the mass flow at each station is different and the nozzle may or may not be choked. The model postulated by Continuum in Ref. 1 was that the total pressure, total temperature, flow angle, and instantaneous static pressure at the inlet be specified as unsteady boundary conditions.

The VAST code treats 2- or 3-dimensional transient gas flows either inviscidly or viscously. To predict turbulent flows, point values of eddy viscosity must be specified. The VAST code does not require a high density of node points to produce a stable solution; however, the accuracy of the solution is somewhat affected by the grid density used.

SSME geometry has been fitted with several computational grids to set up cases for a transient analysis. In order to choose the specific grid used for detailed computations, the prediction of the supersonic, inviscid, steady flow in the SSME nozzle was made with Continuum's VAST code and was compared to a method-of-characteristics (MOC) prediction. The MOC solution is accepted as an accurate solution of this flowfield. Ideal gas properties were used for this comparison. A straight sonic line at the throat and a linear distribution of flow angles between the centerline and wall tangent were used as upstream boundary conditions. The results of a comparison of these solutions is shown in Fig. 1 for both pressure and Mach number distributions.

The VAST solutions were generated by time integrations from arbitrary initial conditions until a steady state was reached. The first calculations made for this problem showed bounded oscillations in pressure and velocities along the nozzle centerline. These oscillations were probably computational noise and were removed by performing a sufficient number of computational steps to produce a steady state (about 2000). Another 1500 steps were then performed and the results were averaged over each 100 step interval to produce the final solution.



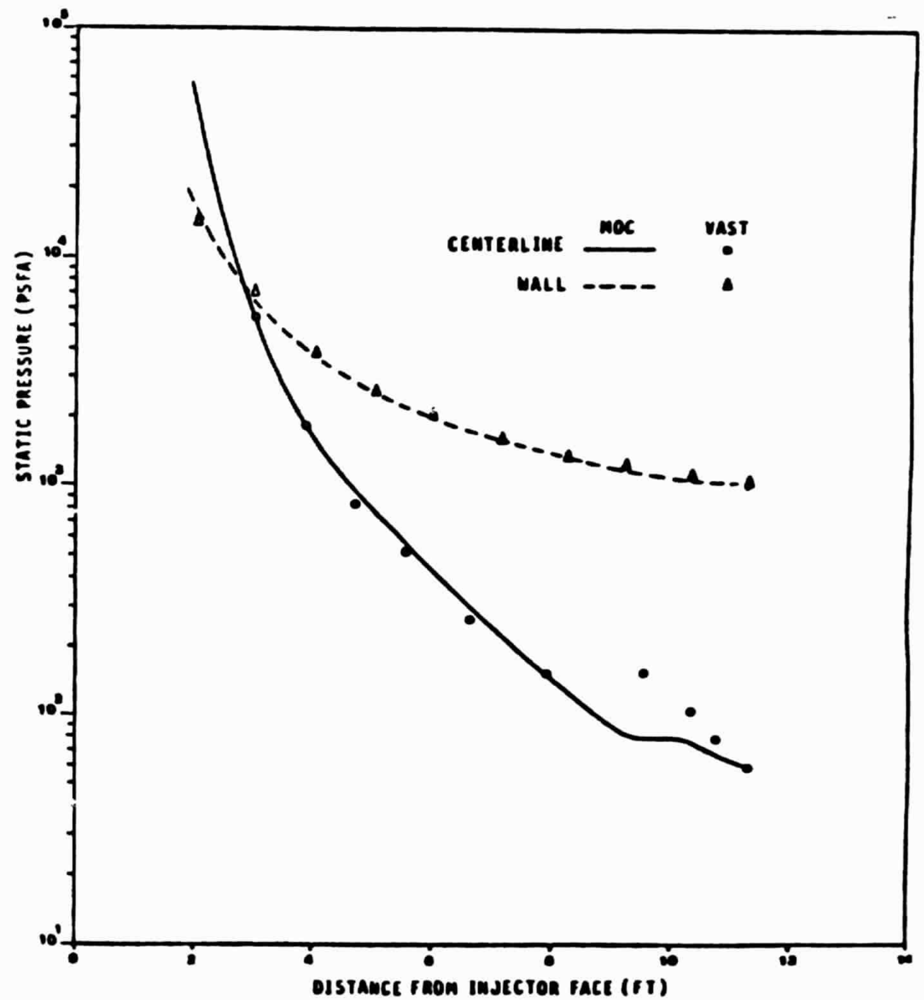


Fig. 1 - Comparison of VAST and MOC Solutions

The pressures shown in Fig. 1 agree very well for both methods of calculation. The slight disagreement around ten feet from the injector face is probably due to the accuracy with which the shock which eminates from the throat wall is predicted. The nature of the MOC solution is such that grid densities are greatly increased along the nozzle wall close to the throat to accurately treat this compressive wave. The VAST solution was obtained for a much more uniform grid, so in this regard the MOC solution is considered to be more accurate. The Mach number on the nozzle wall compares very well with MOC results, however, the Mach number on the nozzle centerline deviates from the MOC results beyond Mach 4.5. This phenomena is not understood and is still the subject of ongoing research. Increasing the grid density by a factor of two does not markedly change this predicted Mach number behavior.

In summary, the pressure solutions from the VAST and MOC codes compare very well and the Mach number solution on the nozzle centerline deviates substantially for the high expansions for the SSME. This deviation was not expected and an in-depth study of its cause was beyond the scope of this contract. The phenomena is still being investigated by Continuum. The excellent pressure comparison suggests that the VAST code can be developed into a very useful tool for SSME nozzle flow predictions.

3. DISCUSSION OF IUS FAILURE

Several failure mechanisms were considered in the IUS problem, but some were discarded as unlikely to create the exhibited anomalies. Discarded were failures of deployment of the inner and outer extensions. Had they not deployed, and the system was still symmetrical then no effect would be noted except a drop in vehicle acceleration. Since the primary evidence was the nozzle gimbal displacement an asymmetric deployment scenario would have to be considered. Significant undeployed nozzle/jet exhaust interaction would be required to overload the control system. Thus, this possible mechanism was discarded in favor of more likely candidates.

The next failure mechanism considered was that of a perforated nozzle. One inch diameter perforations would considered to exist at 10 in. and a 20 in. downstream of the nozzle throat. Calculations were performed to simulate the side jet resulting from such perforations at those locations. The analysis assumed locally two-dimensional flow past an orifice at flow conditions representative of 10 in. and 20 in. aft of the throat.

The nozzle wall conditions adjacent to the hole were taken from a supersonic characteristic analysis and uniform parallel flow was assumed to apply locally. The flow conditions adjacent to the upstream hole were taken to be:

Local Flow Conditions

Hole Position 1	Hole Position 2	Description
2.392	3.65	Mach Number
1915.200	589.00	Pressure psf
2940.000	2210.00	Temperature R
1.307	1.329	Ratio of Specific Heats

The Continuum VAST code was used to perform the calculation of the gas flowfield. Figure 2 shows the flow vectors resulting from postulated hole #1, and there is very little retrograde flow. Figure 3 illustrates the pressure distributions resulting from the analysis. The side forces generated by this hole are too small to be significant. Figures 4 and 5 give the results for hole #2 at 20 in. downstream of the throat.
For this case considerably retrograde motion exists. The hole is further downstream however, which would reduce the impingement loads. It would appear, therefore, that a perforation of this size would not:

a) generate enough side load to saturate the control forces, and
b) that very little impingement on the actuating mechanism (such that proper deployment would be jeopardized) occurs.

The third and final failure mode considered is that a piece of the solid motor dislodged or that the grain was fractured asymmetrically. Such a failure would (possibly)

a) generate considerable side force;
b) generate higher than design thrust;
c) approach normal characteristics at long time (near burn out).

An analysis approximating the IUS situation was performed to demonstrate that a considerably detailed analysis could, if necessary, be performed. Figure 6 illustrates the

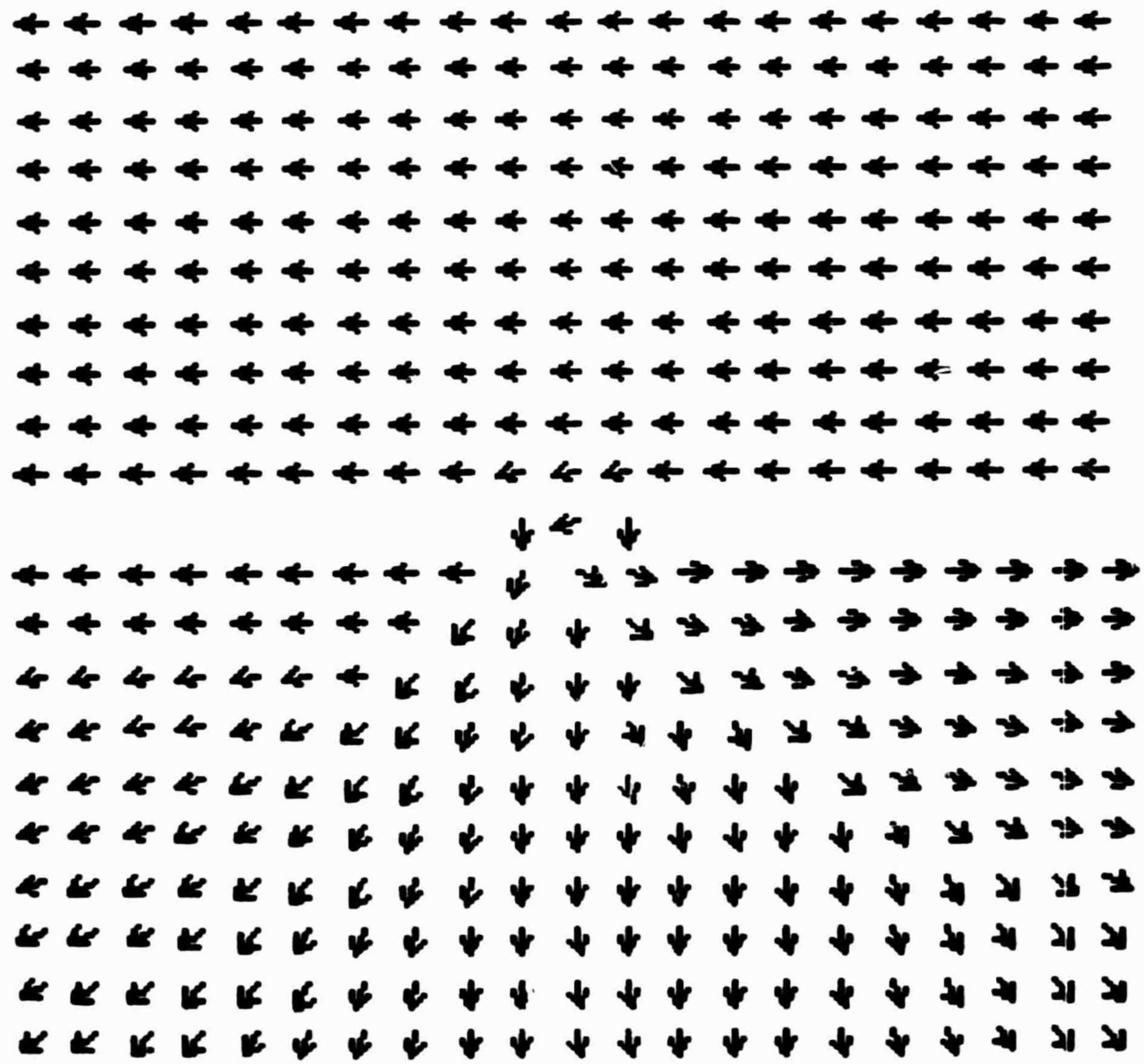


Fig. 2 - Velocity Vectors for Perforation 10 in. Downstream of Throat

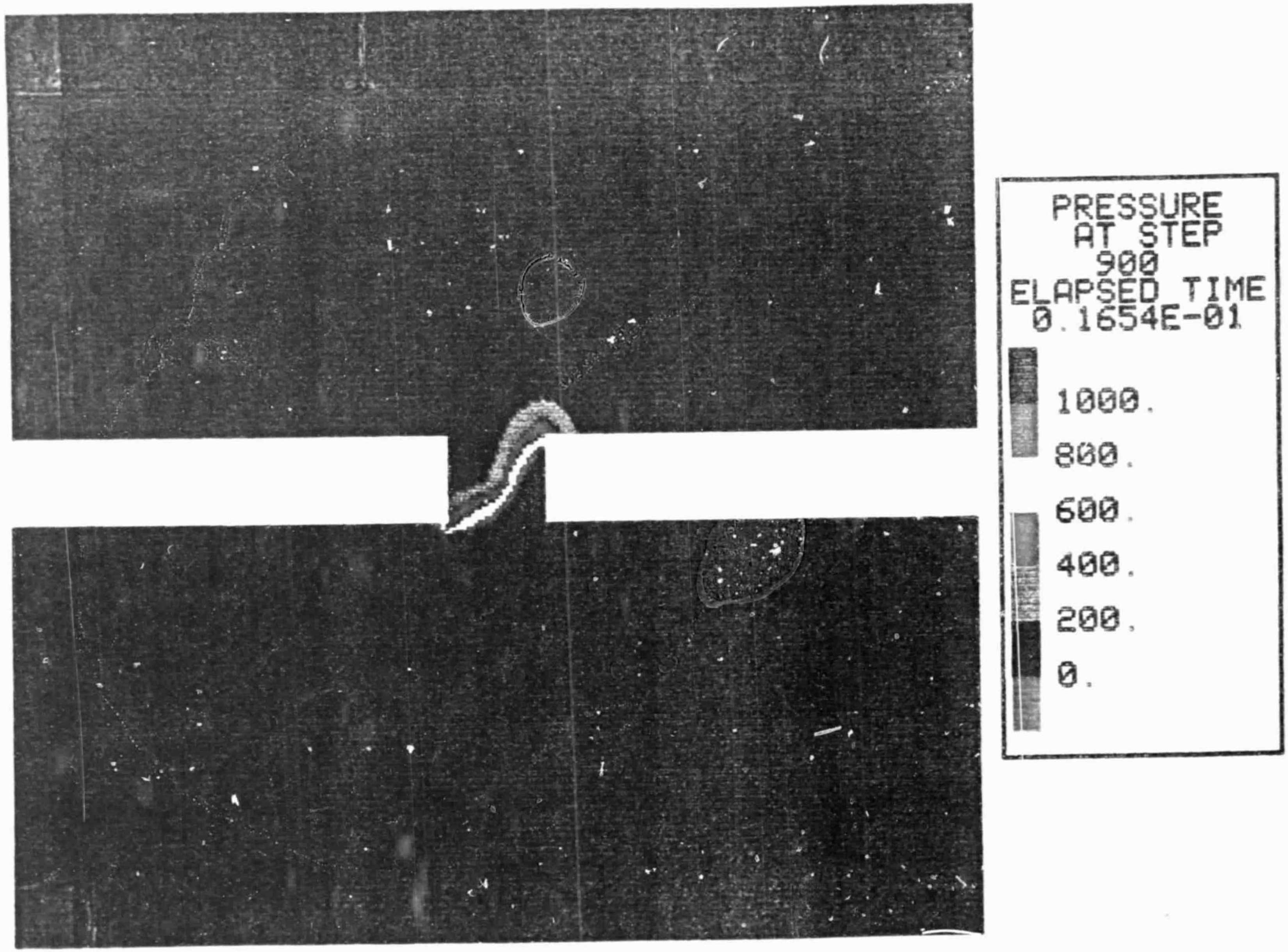


Fig. 3 - Pressure Distribution for Perforation 10 in. Downstream of Throat

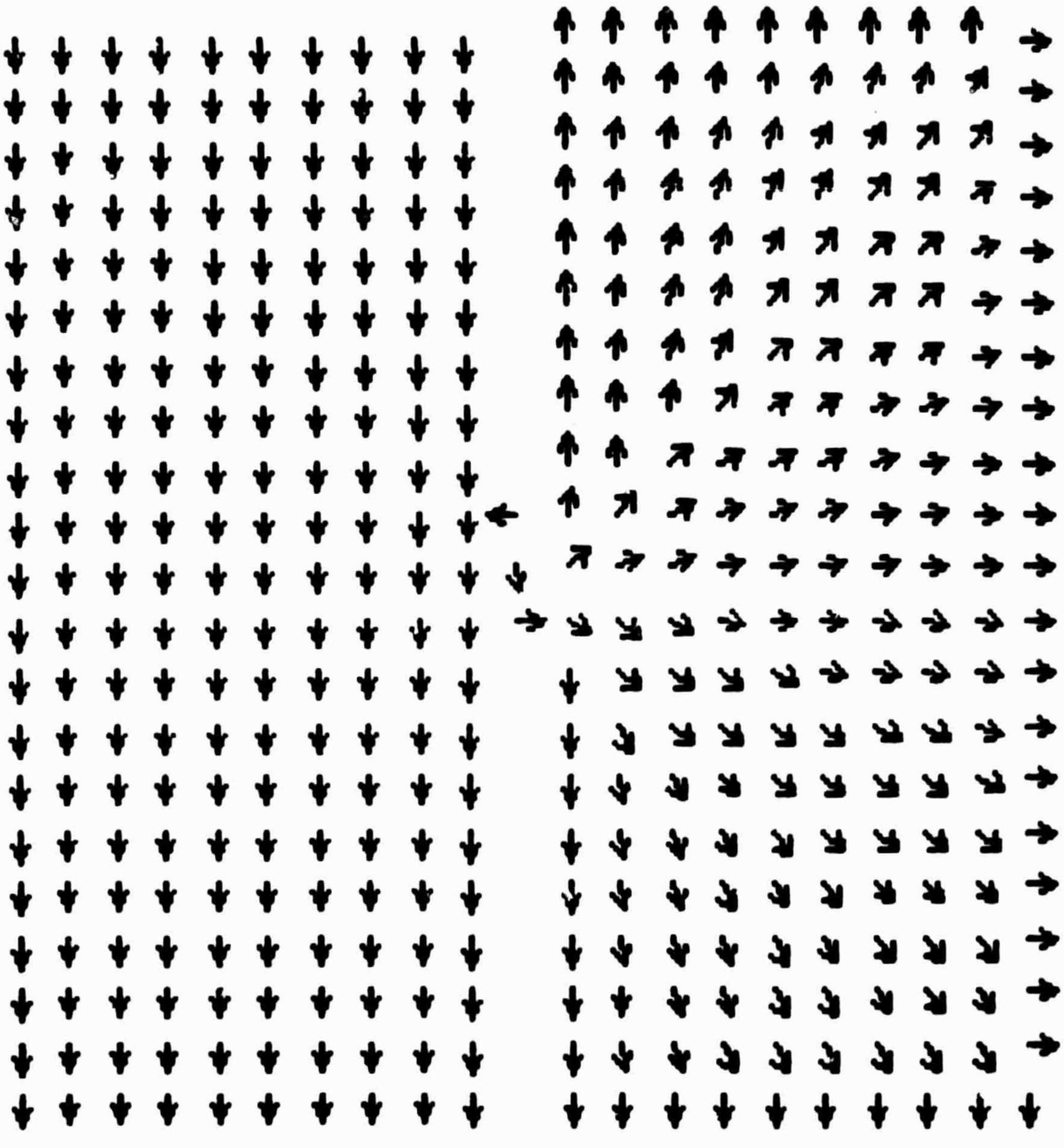


Fig. 4 - Velocity Vectors for Perforation 20 in. Downstream of Throat

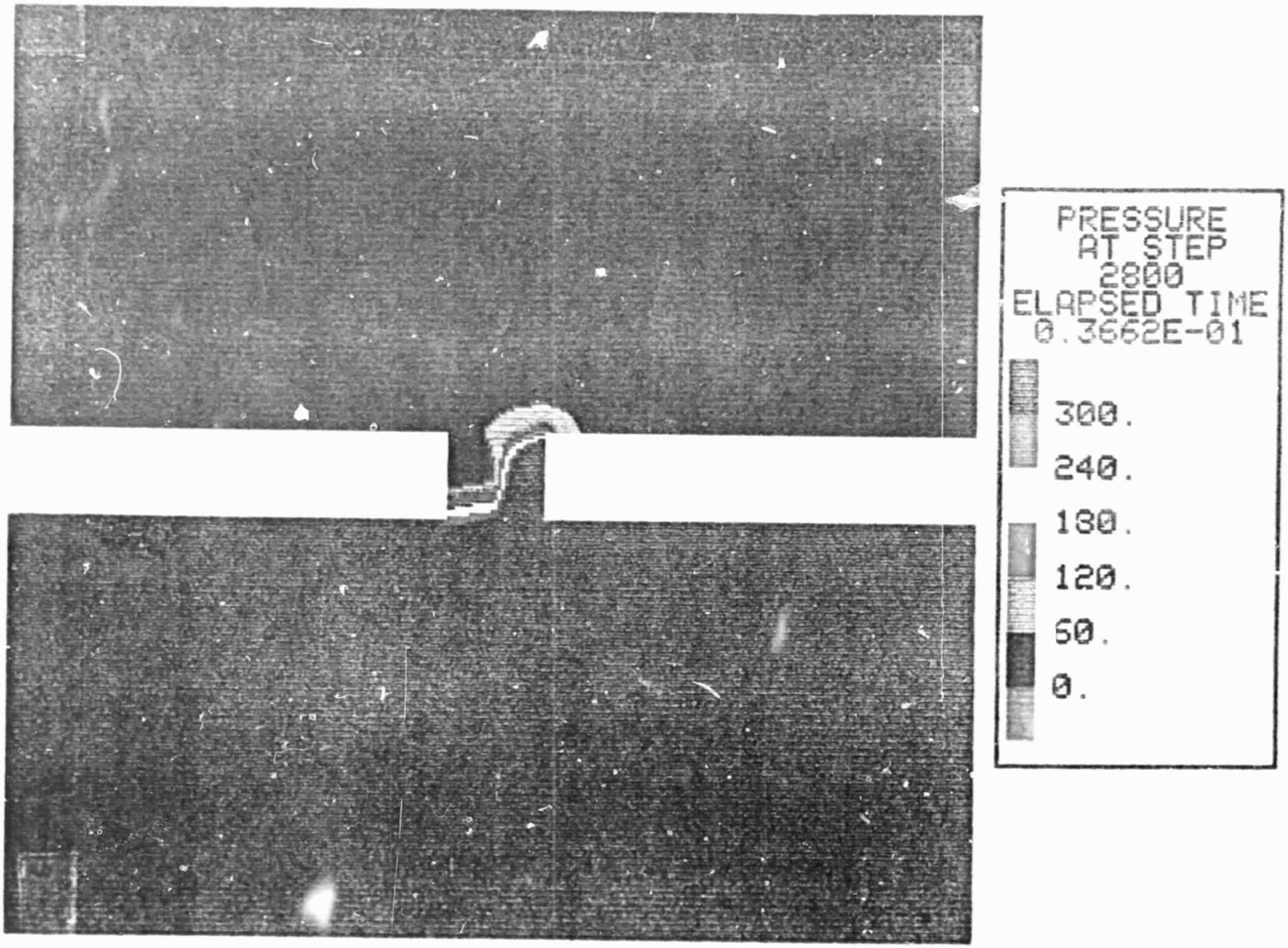


Fig. 5 - Pressure Distribution for Perforation 20 in. Downstream of Throat

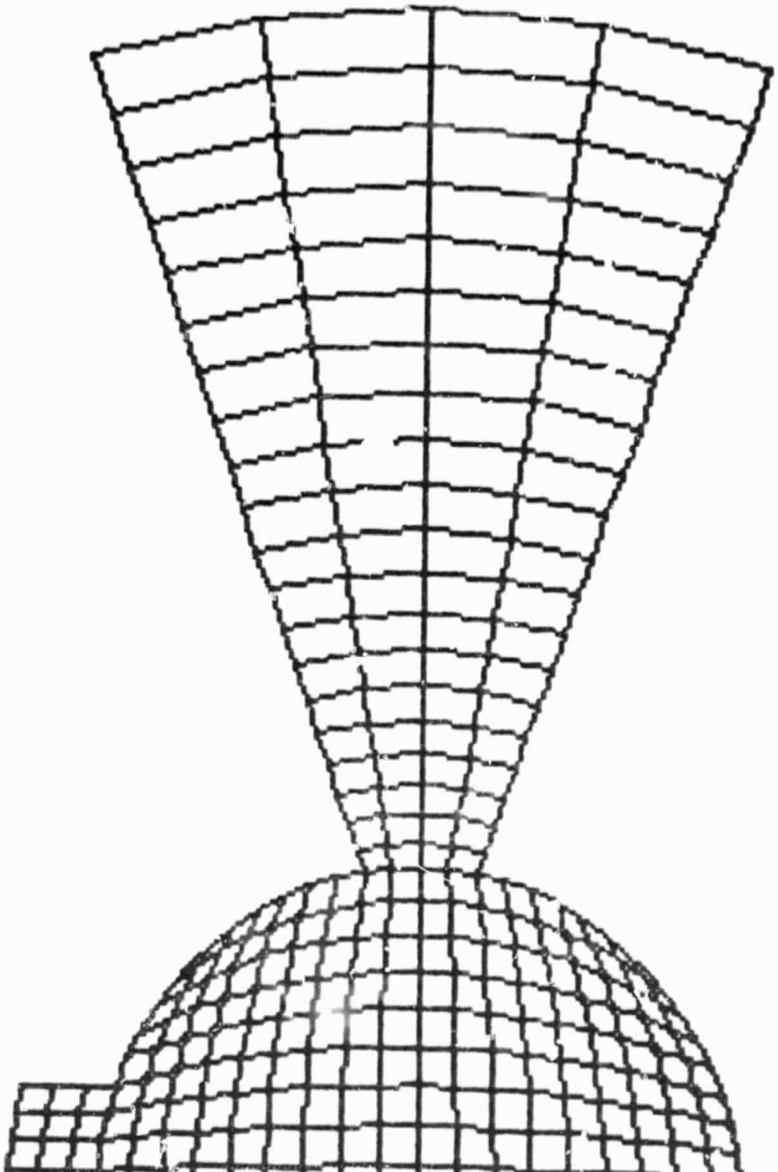


Fig. 6 - Grid Distribution for Damaged Combustor

grid used in this analysis. The grain was made spherical and the nozzle conical for simplicity. The burn area was increased by removing a section of the grain. Thus the burn area has been increased and the problem has become asymmetric. An increased burn rate per unit area could have been used to simulate a cracked grain without dislodging the mass. Depending on the severity of the cracking, and where it occured, very large side forces and increases in thrust could occur. It would, therefore, appear that grain cracking and/or dislodgement is a likely candidate to explain the IUS failure.

Figure 7 shows the velocity distribution that results from this analysis. The velocity vectors are color coded green, magenta, yellow, red, black in order of increasing speed. Only small asymmetrics are noted. It is likely, therefore, that the failure noted is more likely due to cracking than to actual dislodgement.

4. CONCLUSIONS

A transient analysis of the SSME has been set up for further analysis. The grid density required has been determined. Some areas of code refinement have been identified for further study.

Grain cracking and/or dislodgement were identified as a possible single failure mechanism which would satisfy the observables.

5. REFERENCES

1. Continuum, Inc., "Transient and 3-D Rocket Engine Analysis", Final report on NAS8-35846, (Huntsville, AL, May 1984).

Fig. 7 - Velocity Vectors Resulting from Damaged Combustor

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